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Advances in Modeling Exploding Bridgewire Initiation

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Abstract. There is great interest in applying magnetohydrodynamic (MHD) simulation techniques to the designs of electrical high explosive (HE) initiators, for the purpose of better understanding a design's sensitivities, optimizing its performance, and/or predicting its useful lifetime. Two MHD-capable LLNL codes, CALE and ALE3D, are being used to simulate the process of ohmic heating, vaporization, and plasma formation in exploding bridgewires (EBW). Initiation of the HE is simulated using Ignition & Growth reactive flow models. 1-D, 2-D and 3-D models have been constructed and studied. The models provide some intuitive explanation of the initiation process and are useful for evaluating the potential impact of identified aging mechanisms (such as the growth of intermetallic compounds or powder sintering). The end product of this work is a simulation capability for evaluating margin in proposed, modified or aged initiation system designs.

Introduction

This work builds upon previously reported work in modeling the performance of new and aged EBWs.[1] Present models of EBW detonators include Ignition and Growth (I&G) Reactive Flow Models for the initiating explosive (most commonly PETN),[2] and the response of the explosive is dynamically coupled with the excitation from the EBW. Most of our early work has been in the exploration of simple one- and two-dimensional models of EBWs with PETN using the two-dimensional LLNL-developed hydrodynamic code CALE. Simple 1-D models, in particular, lend some basic insight into how EBW detonators function – how electrical energy is converted to heat, changing the phase of the EBW so quickly that it explodes and sends shocks into the surrounding medium (PETN). Some of these basic insights are discussed here, and more complicated models of other geometries (such as EBFs and slappers) are introduced as our current and future work.

EBW Modeling Methods & Results

Figure 1 shows basic output from a typical 1-D CALE model of a gold EBW surrounded by half-dense PETN. A convenient method for displaying such results is the "streak plot" where the variable of interest (density, pressure, etc.) is plotted as a function of space (radius, in the y-direction) and time (in the x-direction). This shows the geometry of the EBW-PETN system at all times, as well as the variable of interest at all locations in the model. Though the 1-D models are simplified, they lend insight into the dynamics of EBW detonator function. In general, the EBWs in these models experience four "phases" that appear distinct in these simple models though are more blurred in real detonator function. The first of these phases is the "heating phase" (occurring for this geometry up through 540 ns), during which the current density builds, causing ohmic heating of the EBW. The resistance grows slowly until the EBW melts, causing the resistance to grow more rapidly until the vaporization temperature is reached. At this temperature, the "vapor expansion phase" (540-720 ns) begins, as the gold vaporizes and begins seeking a lower density, sending a relatively weak shock into the surrounding PETN. In these simple models, the latent heat of vaporization is neglected, thus vaporization is instantaneous (an obvious discrepancy with experimental observations), but the result of vastly increased EBW resistance and a spike in bridge voltage ("burst") is captured. The vapor expansion phase is marked by decelerating expansion of the gold gas with density moving to the wire exterior, still heating as the plasma formation temperature is approached. At this point, the "plasma expansion phase" (720-940 ns) begins, and the EBW exhibits an accelerating runaway expansion as the EBW grows to large diameters as a thin tube of gold plasma that is continually decreasing in density as the circuit current builds to its maximum. It is during this phase that the EBW sends its largest, fastest shocks into the PETN. The peak circuit current marks the beginning of the final "collapse / recovery phase" (beyond 940 ns) as the current decays (recovers) and the plasma collapses inward due to forces induced by the existing magnetic field. These basic phases of EBW dynamics appear in all our typical EBW simulations.

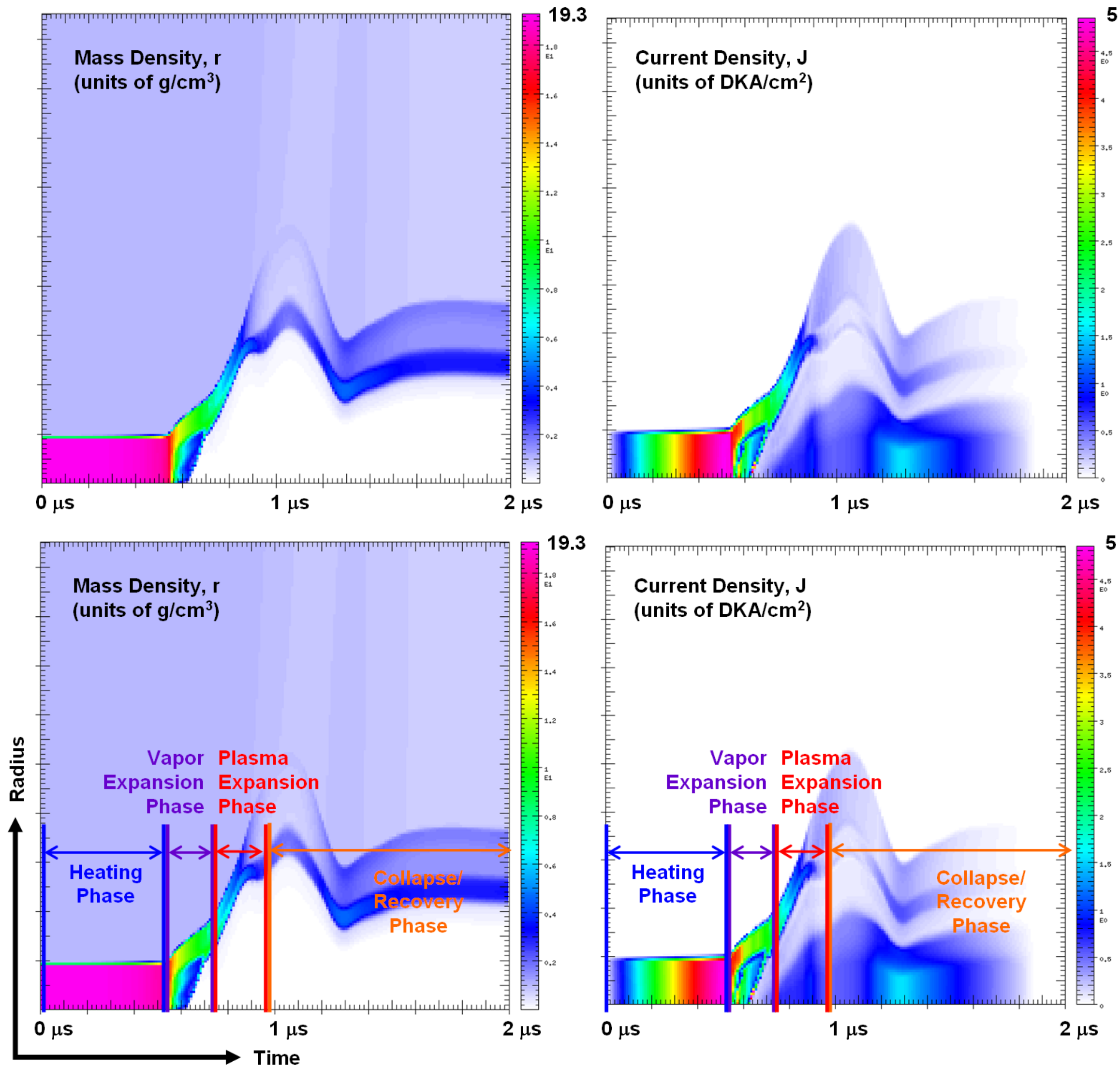

Figure 1. Streak plots showing basic one-dimensional EBW dynamic trends. Left panels show density plotted as a function of radius and time; right panels show current density. Bottom panels include labels for qualitative EBW dynamic "phases" (discussed in text).

Figure 2 demonstrates a qualitative comparison between electrical waveforms as observed in experiment, and as simulated by CALE in these 1-D models. The biggest discrepancy is the neglect of the latent heat of vaporization, and the early spike in voltage that produces. Also, because less energy is drained from the circuit during vaporization, a larger current peak results. Though not shown here (for brevity), experimental streak images of exploding wires show the same weak vaporization shock, followed by strong plasma-formation shocks as are seen in these simulations. The fact that multiple shock waves of increasing strength and speed are emitted from the EBW is important in understanding how the surrounding powder is initiated.

The dynamics of the EBW is largely unaffected by the surrounding powder because the time scale of the EBW dynamics is significantly shorter than the powder reaction. The powder, however, is entirely driven by the shocks sent into it by the EBW. Figure 3 shows more streak-plot simulation results, but at the scale of the powder (much larger than the EBW). Most noteworthy is the fact that near the EBW, the powder initiates very slowly, taking about half a microsecond to completely initiate, and the further away from the EBW, the faster initiation occurs. This is because the earlier shocks are weaker and slower, and are swept up by and combine with the later, stronger shocks. The net result is a stronger, faster initiation, away from the bridge, after the contributing shocks have coalesced. This is further enhanced by contributing pressures from partial reactions of the powder. The powder initiation completes away from the bridge first, and to some extent burns backward toward the EBW. This build-up of initiation is in qualitative agreement with LLNL experiments on "cut-back" detonators (not shown here, for brevity).

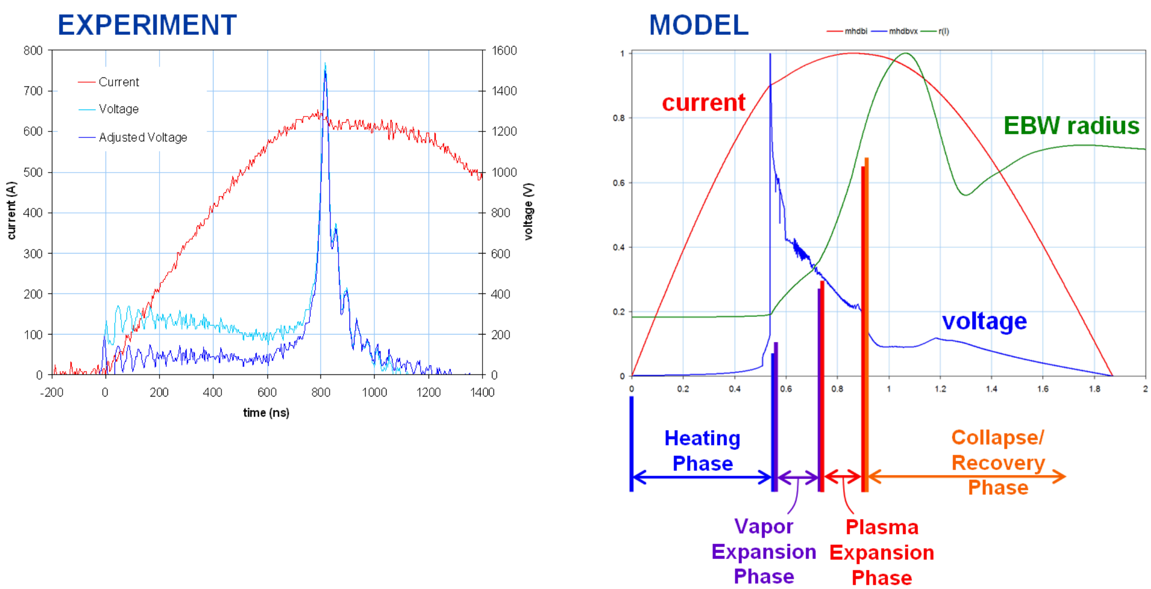

Figure 2. Qualitative comparison of experimental results with 1-D model. "Phases" are divided by electrical or hydrodynamic events, which appear instantaneous in models, but in reality are smeared over time and not so distinct. The measured voltage is "adjusted" to remove induced voltage effects, allowing a more direct comparison. Wiggles or jitter in the experimental waveforms are not only due to diagnostic uncertainties, but to transmission line effects, which are not simulated.

Ultimately, some distance away from the EBW, a steady state detonation of the PETN occurs, and initiation occurs as quickly as possible. If one were to trace back from this outer region inward to the instant in time when a prompt initiation of the powder would have had to occur at the EBW-PETN interface (found by tracing the steady state slope back toward zero radius – approximately 1 microsecond in this example), this instant is delayed relative to the burst time (which should be about 750 ns in the example, but is premature due to neglect of latent heats). This 250 ns of time is the so-called "EBW lost time" or "excess transit time" that is often referred to in classic EBW texts.[3,4] It represents the increased amount of time this gradual acceleration of initiation requires relative to what would be needed for prompt initiation at the EBW-powder interface.

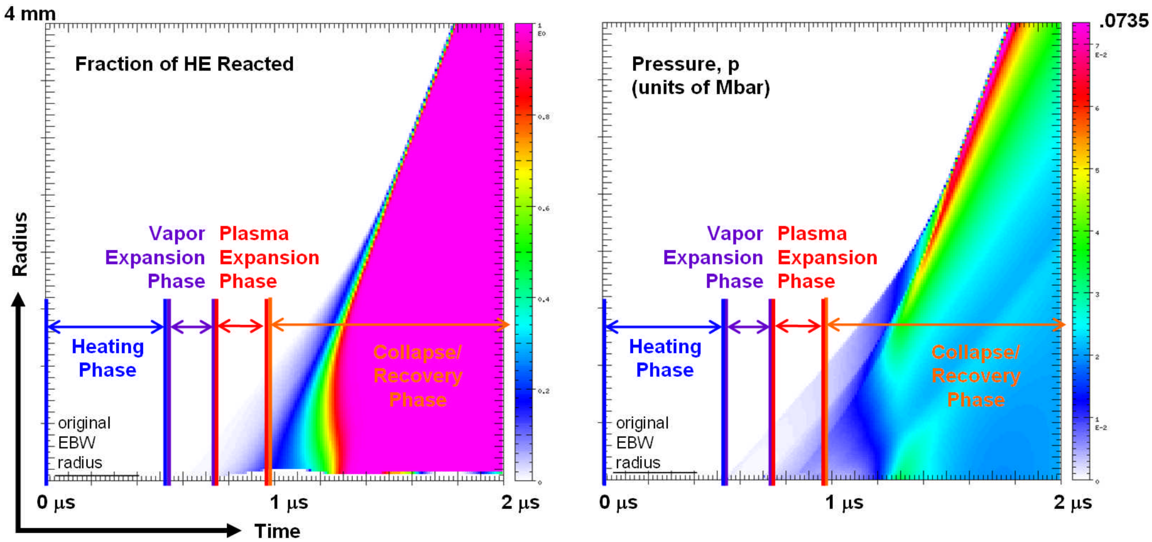

Figure 3. 1-D model results of powder response to EBW burst. Note that the vertical (distance) scale is much larger than in Figure 1, and that the EBW itself occupies only a small volume at small radii. The left panel shows fraction of HE reacted, and that near the EBW the reaction is slow, occurring more quickly some distance away from the EBW. The right panel (pressure) shows the coalescence of pressure waves some distance away from the EBW, and that a steady state detonation wave does not occur until about 1.5 microseconds after excitation begins. This acceleration of the initiation has been seen in LLNL experiments.

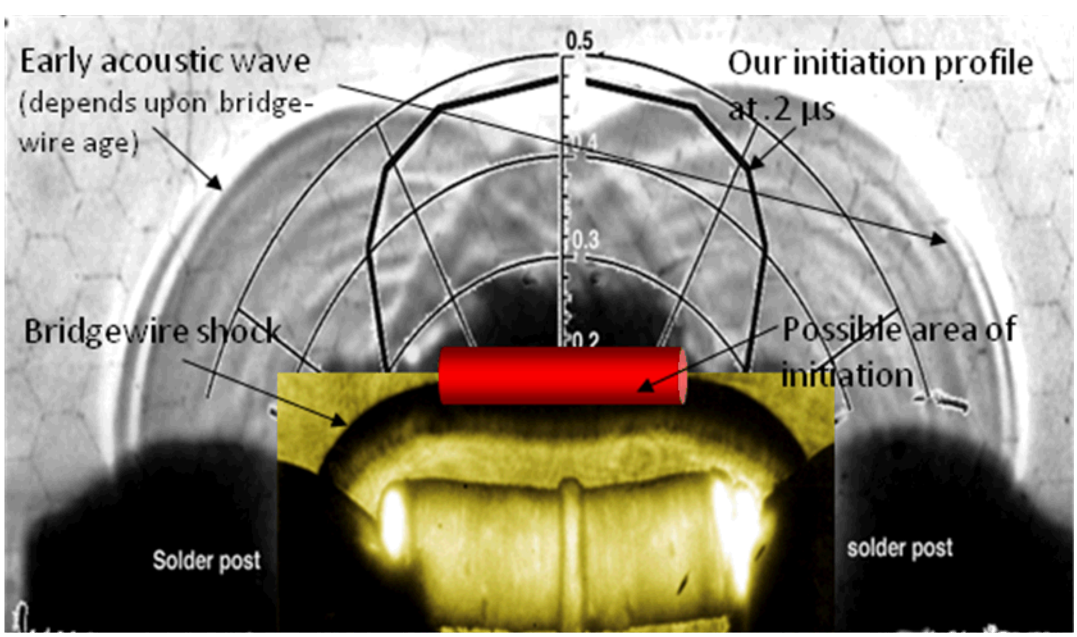

Figure 3A. Overlay image from Roeske, Benterou, et al. showing that initiation occurs some distance away from the bridgewire, found by tracing initiation profiles backward in time toward their origin, thought to be about 0.2 mm away from the EBW.

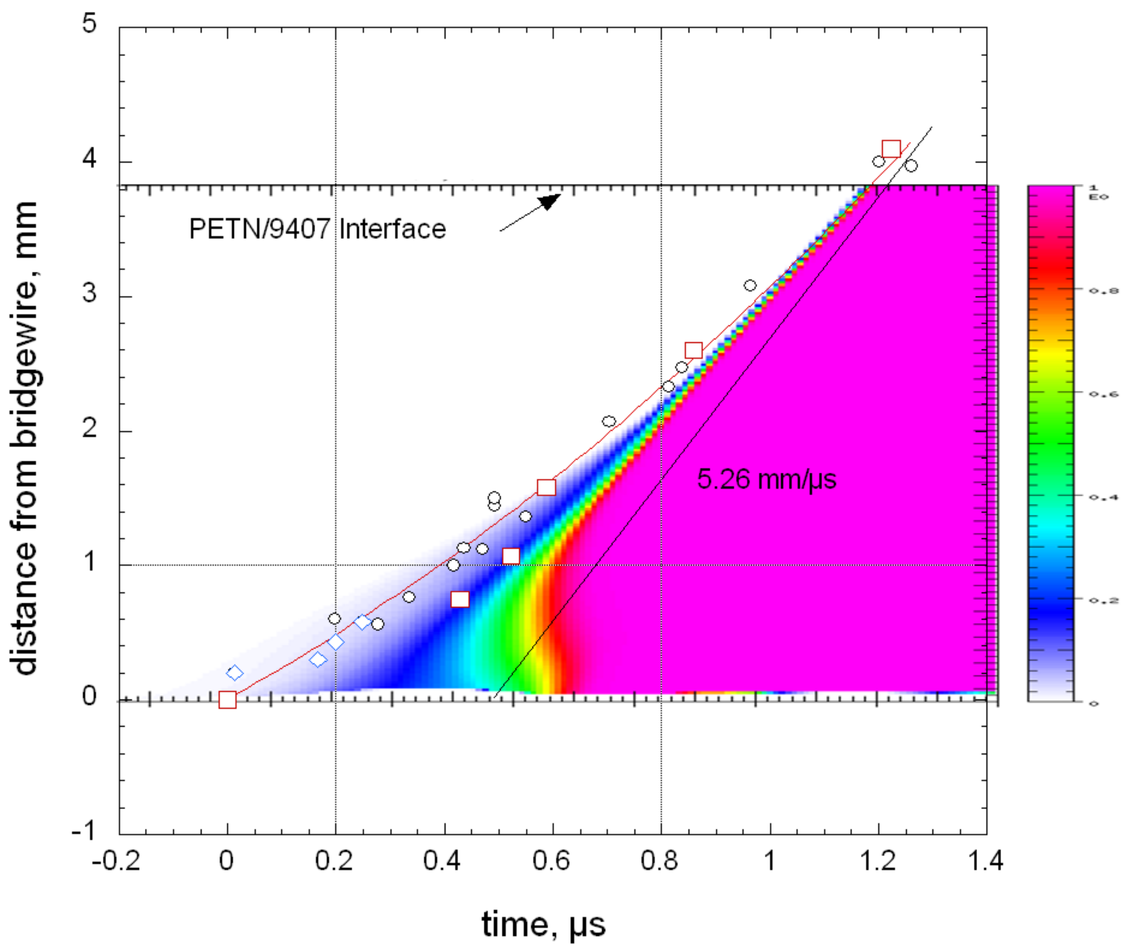

Figure 3B. Overlay image showing results from EBW simulations (shading depicting fraction of HE burned) against the breakout time results from the cutback detonator experiments of Roeske, Benterou, et al. Qualitative agreement is observed. In partuclar, full initiation completes some distance away from the EBW (about 1mm away, according to the calculations, and initiation completes faster away from the EBW, causing the accelerating trend in the Roeske, et al. results.

Figure 3A is an illustration of the key findings from earlier work done by F. Roeske, J. Benterou, and R. Lee of LLNL, which demonstrated that initiation in EBW detonators occurs some distance away from the bridgewire in the powder. This team was able to show this by milling down EBW detonators from the top (spherical side) using their femtosecond laser apparatus. In Figure 3B, their quantitative results for breakout times of their partial detonators show that the speed of the shock to detonation transition starts slowly, then builds gradually to full detonation speed. This is the experimental concept of "lost time" in EBW detonators.

Figure 4 summarizes the concept of the EBW lost time in diagrams. If an EBW-powder system is overdriven – that is, the shocks from the EBW are stronger and faster than steady state powder detonation – prompt initiation is expected and there is no lost time. When under-driven, the need for multiple shocks to coalesce to initiate the powder arises. As excitation decreases, this requires more space (resulting in apparent initiation further away from the EBW) and more time (the EBW lost time). At sub-threshold excitations, the shocks die out before they can effectively coalesce and initiate the powder.

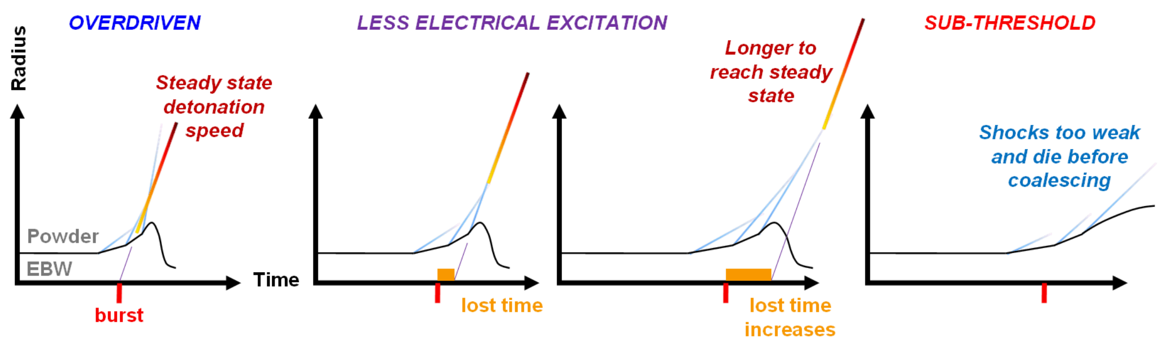

Figure 4. Basic explanation for EBW "lost time." When the system is overdriven (left) the shocks into the HE are faster than the steady state detonation speed of the powder, and there is essentially no time "lost" between burst and powder detonation. As excitation decreases, the dynamic processes of EBW burst slow down, and it takes more time (and more distance) for the EBW shocks to combine and become strong enough to light the powder (away from the EBW). This manifests itself as "lost time" due to delayed onset of steady state detonation. At sub-threshold excitations (right), the shocks die before they can combine to be strong enough to light the powder.

Three-Dimensional EBW Modeling

Significant insight and information can be obtained from 2D and even 1D analyses of these systems. However, these systems are inherently three-dimensional and therefore must be modeled as such to capture all relevant details. Of particular interest are: (1) the effect of the header on the initiating EBW shock, (2) effects due to the finite length of the EBW, and (3) the predicted shape of the expanding EBW plasma after burst. Current efforts in modeling are therefore focused on extending existing 1D and 2D models to full 3D analyses. The LLNL-developed hydrocode ALE3D is being utilized in this effort due to its advanced fully coupled MHD capability.

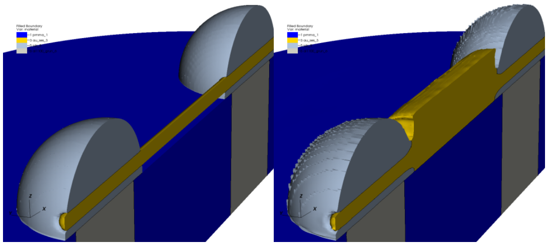

Figure 1: A basic 3D EBW analysis (left: initial configuration; right: after burst).

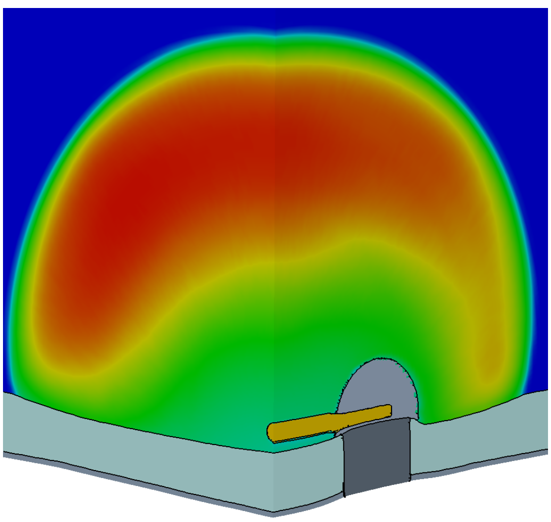

Figure 2: 3D analysis of gold EBW initiating half-dense PETN (Tarver I&G). Different shades depict different levels of HE reaction in the surrounding PETN. Consistent with 1D analyses, the 3D analyses show initiation completing first at some distance away from the bridgewire (about 1mm) as opposed to at the bridgewire.

While significant room for improvement exists, and will be pursued, these simple EBW models suggest a basic framework for how EBW-mode powder initiation occurs in common EBW detonators. Meanwhile, EBW models have been generalized to more complicated geometries for a variety of different sensitivity studies.   Fully-coupled MHD initiator simulations using finite element codes such as these are still fairly new at LLNL, and gaining more interest and potential applications. The insight provided from even the simplest of models appears valuable, as well as predictions from more specifically tailored analyses.

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